REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
07-08-2013	Final Report	15-Nov-2007 - 14-Apr-2013

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Disordered Quantum Gases and Spin-Dependent Lattices	W911NF-08-1-0021
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 7D10AJ
6. AUTHORS Brian DeMarco	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
University of Illinois - Urbana - Champaign c/o OSPRA Board of Trustees of University of Illinois Urbana-Champaig Champaign, IL 61820 -7406	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 54047-PH-DRP.11

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

This grant supported the first realization of the disordered Bose-Hubbard models using ultra-cold atoms trapped in a disordered optical lattice. Several critical questions regarding this crucial paradigm of granular superconductors were addressed. A superfluid-to-insulator transition was studied via transport measurements, and interactions were found to screen the effect of disorder on the superfluid phase. Using measurements of condensate fraction, a Mott insulator to re-entrant superfluid transition was found to be absent. Anderson localization in 3D for matter waves

15. SUBJECT TERMS

ultracold gases, quantum gases, disordered solids, Hubbard model

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Brian DeMarco
UU	UU	UU	UU		19b. TELEPHONE NUMBER 217-244-9848

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Disordered Quantum Gases and Spin-Dependent Lattices

ABSTRACT

This grant supported the first realization of the disordered Bose-Hubbard models using ultra-cold atoms trapped in a disordered optical lattice. Several critical questions regarding this crucial paradigm of granular superconductors were addressed. A superfluid-to-insulator transition was studied via transport measurements, and interactions were found to screen the effect of disorder on the superfluid phase. Using measurements of condensate fraction, a Mott insulator to re-entrant superfluid transition was found to be absent. Anderson localization in 3D for matter waves was also observed for the first time, and the first measurements of how the mobility edge depends on disorder strength were carried out. Finally, this grant supported studies of spin-dependent lattices, including the first demonstration of mixed superfluid and Mott insulator phases.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/26/2013	2.00	W. R. McGehee, S. S. Kondov, J. J. Zirbel, B. DeMarco. Three-Dimensional Anderson Localization of Ultracold Matter, Science, (10 2011): 0. doi: 10.1126/science.1209019
07/26/2013	3.00	M. Pasienski, D. McKay, M. White, B. DeMarco. A disordered insulator in an optical lattice, Nature Physics, (07 2010): 0. doi: 10.1038/nphys1726
07/26/2013	4.00	M. White, M. Pasienski, D. McKay, S. Q. Zhou, D. Ceperley, B. DeMarco. Strongly Interacting Bosons in a Disordered Optical Lattice, Physical Review Letters, (02 2009): 0. doi: 10.1103/PhysRevLett.102.055301
07/26/2013	5.00	D McKay, B DeMarco. Thermometry with spin-dependent lattices, New Journal of Physics, (05 2010): 0. doi: 10.1088/1367-2630/12/5/055013
07/26/2013	7.00	D. McKay, M. White, B. DeMarco. Lattice thermodynamics for ultracold atoms, Physical Review A, (06 2009): 0. doi: 10.1103/PhysRevA.79.063605

TOTAL: 5

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Stan Kondov, Three-Dimensional Anderson Localization of Ultracold Matter, Physics of Quantum Electronics (2012)/Talk

David Chen, David McKay, Carolyn Meldgin, Brian DeMarco, Reservoir-Assisted Band Decay of Ultracold Atoms in a Spin-Dependent Optical Lattice, DAMOP (2012)/Talk

Carolyn Meldgin, David Chen, Brian DeMarco, Spatially Selective Imaging in a Three-Dimensional Optical Lattice, DAMOP (2012)/Poster

Brian DeMarco, Three-Dimensional Anderson Localization of Ultracold Matter, DAMOP (2012)/Talk

William McGehee, Stanimir Kondov, Joshua Zirbel, Brian DeMarco, 3D Anderson Localization in Variable-Scale Speckle Potentials, DAMOP (2012)/Talk

Stanimir Kondov, William McGehee, Joshua Zirbel, Brian DeMarco, Disordered Hubbard Model with Ultracold Atoms, DAMOP (2012)/Talk

David Chen, Cecilia Borries, Matthew White, Brian DeMarco, Quantum Quenches in a Strongly Correlated Optical Lattice, DAMOP (2011)/Talk

William McGehee, Stanimir Kondov, Joshua Zirbel, Brian DeMarco, Progress Toward the Disordered Hubbard Model, DAMOP (2011)/Poster

Joshua Zirbel, Stanimir Kondov, William McGehee, Brian DeMarco, Anderson Localization of Ultracold Fermionic K, DAMOP (2011)/Talk

Carolyn Meldgin, Matthew Pasienski, Brian DeMarco, Atomic Magnetic Resonance Imaging in an Optical Lattice, DAMOP (2011)/Talk

Brian DeMarco, Strongly Correlated Quantum Gases Trapped in 3D Spin-Dependent Optical Lattices, APS March Meeting (2011)/Talk

David McKay, Brian DeMarco, Thermalization in 1D, 2D, and 3D Spin-Dependent Lattices, DAMOP (2010)/Talk

David Chen, Cecilia Borries, Carolyn Meldgin, Brian DeMarco, Quantum Quenching in an Optical Lattice, DAMOP (2010)/Poster

Joshua Zirbel, Stanimir Kondov, William McGehee, Brian DeMarco, Fermions in a 3-D Disordered Potential, DAMOP (2010)/Talk

Matthew Pasienski, Carolyn Meldgin, Brian DeMarco, Spatially Resolved Compressibility Measurements in the Disordered Bose-Hubbard Model , DAMOP (2010)/Poster

Fei Lin, ShengQuan Zhou, Matthew Pasienski, Brian DeMarco, David Ceperley, Quantum Monte Carlo Simulation of Disordered Bose-Hubbard Model in a 3D Optical Lattice, APS March Meeting (2010)/Talk

Brian DeMarco, Experiments on Disordered Quantum Gases, APS March Meeting (2010)/Talk

Brian DeMarco, Transport Measurements in the Disordered Bose-Hubbard Model, DAMOP (2009)/Talk

David McKay, Brian DeMarco, Lattice Thermodynamics for Ultra-Cold Atoms, DAMOP (2009)/Talk

Matthew White, Matthew Pasienski, David McKay, Brian DeMarco, Experiments on the 3D Disordered Bose-Hubbard Model, DAMOP (2008)/Talk

David McKay, Matt White, Matt Pasienski, Brian DeMarco, Evidence for Metallic Behavior in the Bose-Hubbard Model, DAMOP (2008)/Poster

Matthew Pasienski, Matthew White, David McKay, Brian DeMarco, Noise Correlation Measurements on the 3D Disordered Bose-Hubbard Model, DAMOP (2008)/Poster

Number of Presentations: 22.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
07/26/2013	6.00	D. C. McKay, C. Meldgin, D. Chen, B. DeMarco. Slow Thermalization Between a Lattice and Free Bose Gas, Physical Review Letters (in press) (11 2012)
08/30/2012	1.00	W. R. McGehee, J. J. Zirbel, S. S. Kondov, B. DeMarco. Three-Dimensional Anderson Localization of Ultracold Matter, Science (10 2011)

TOTAL: **2**

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

University of Illinois Willett Faculty Scholar Award (2013).
University of Illinois College of Engineering Excellence in Research Award (2012).
Vestal High School Hall of Fame Inductee (2012).

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Wenchao Xu	0.03	
William McGehee	0.05	
Carolyn Meldgin	0.15	
David Chen	0.15	
Matthew Pasienski	0.30	
Matthew White	0.08	
Philip Russ	0.12	
Stanimir Kondov	0.07	
FTE Equivalent:	**0.95**	
Total Number:	**8**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Brian DeMarco	0.05	
FTE Equivalent:	**0.05**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME	
Matthew Pasienski	
Matthew White	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
Paul Koehring	0.05
FTE Equivalent:	**0.05**
Total Number:	**1**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

The highest impact results supported by this grant are discussed in the text that follows.

Disordered quantum gases

One focus of the work supported by this grant was disordered quantum gases. There are numerous outstanding questions regarding the role of disorder in many-particle quantum systems, such as superconductors and electronic solids. These issues are of great technological importance because disorder can enhance or degrade desired material properties. Our work also impacts fundamental physics, since what quantum phases result through the interplay of interactions and disorder and how disorder impacts quantum dynamics in interacting systems is not understood.

Disordered Bose Hubbard model

By combining optical speckle disorder and a three-dimensional optical lattice, we realized the disordered Bose-Hubbard (DBH) model for the first time. Many open questions revolve around the DBH model, which is a paradigm for granular superconductors. For example, we do not know the 3D DBH model phase diagram at finite temperature, and we do not understand dynamical properties such as transport.

In these experiments, we trap bosonic ^{87}Rb atoms in a cubic optical lattice created from counter-propagating laser beams. Disorder is introduced by passing a 532 nm laser beam through a holographic diffuser and focusing the resulting optical speckle field onto the atoms (Fig. 1). The disorder strength is continuously tunable by adjusting the 532 nm laser power, and the equivalent of the "clean" material parameters can be changed via the lattice laser intensity.

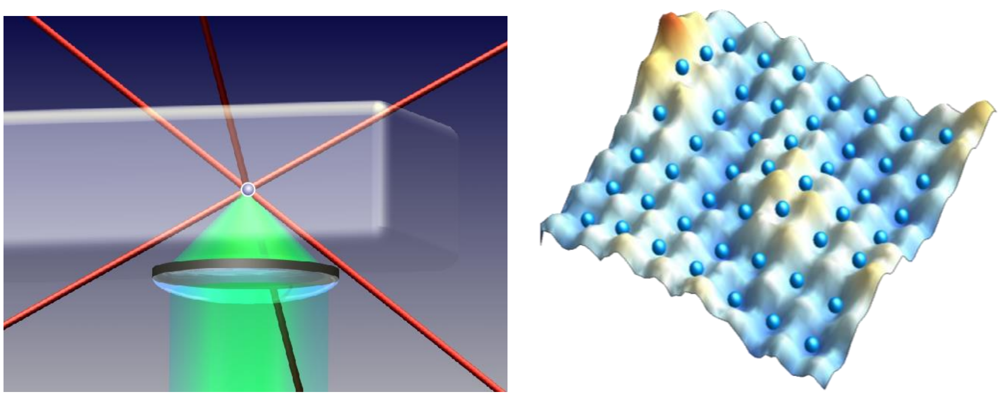

Figure 1. A disordered lattice is formed from three counter-propagating near-infrared laser beams (red) and an optical speckle field (green). The disordering potential can be measured directly using optical microscopy.

M. WHITE, M. PASIENSKI, D. MCKAY, S.Q. ZHOU, D. CEPERLEY, AND B. DEMARCO, STRONGLY INTERACTING BOSONS IN A DISORDERED OPTICAL LATTICE, *PHYSICAL REVIEW LETTERS* **102**, 055301 (2009)

In collaboration with Ceperley's group, we determined the disordered lattice Hubbard parameters (Fig. 2), making our disordered lattice the first example of a quantum "material" where the disorder is precisely known and completely adjustable. We also measured how disorder impacts condensate fraction at high density in the superfluid and Mott-insulator regimes (Fig. 3). We found that condensate fraction was suppressed by increasing disorder, suggesting that the re-entrant superfluid, a unique phase predicted for the DBH model, is not present.

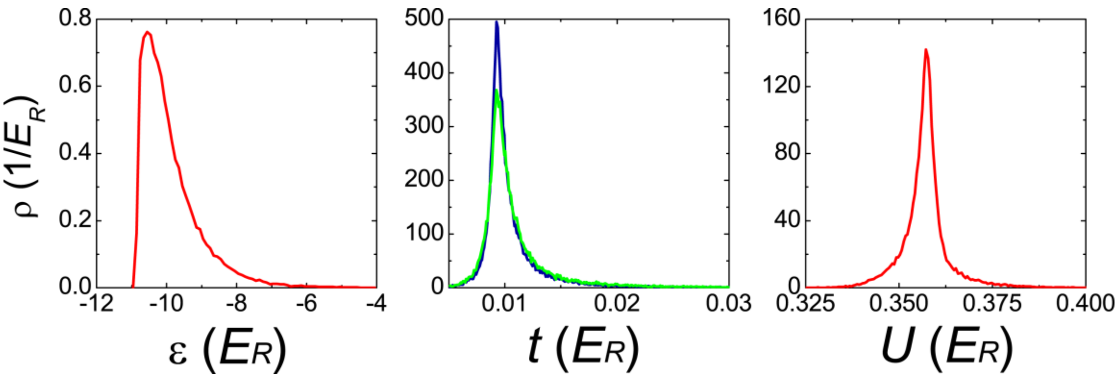

Figure 2. The distribution of Hubbard site energy (ϵ), tunneling (t), and interaction (U) parameters for the disordered lattice.

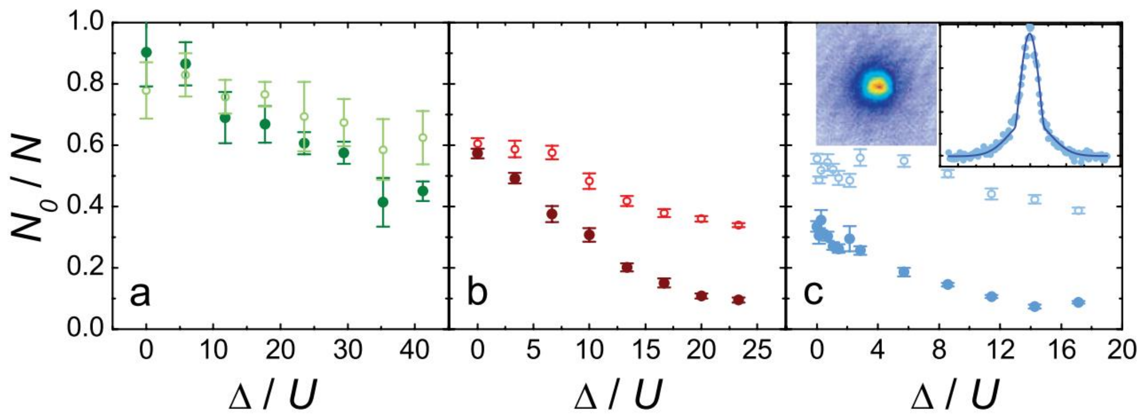

Figure 3. Measurements of condensate fraction N_0/N in the disordered lattice for increasing lattice depth (a-c). The data in (c) are taken for mixed Mott-insulator and superfluid phases (in the clean lattice). The hollow points are taken after slowly turning off the lattice, and demonstrate that disorder introduces negligible heating. The solid points are the condensate fraction measured in the disordered lattice.

M. Pasienski, D. McKay, M. White, and B. DeMarco, A disordered insulator in an optical lattice, *Nature Physics* **6**, 677-680 (2010)

We also investigated transport in the DBH model by applying a force to the atoms and measuring the resulting center-of-mass velocity of the atoms (Fig. 4). We observed that disorder induces a transition to an insulating state for a strongly interacting superfluid. The critical disorder energy required for the transition matches a superfluid–Bose glass transition predicted using state-of-the-art quantum Monte Carlo (QMC) simulations. In the MI regime, we searched for but did not find a disorder-induced

superfluid prediction predicted by QMC calculations.

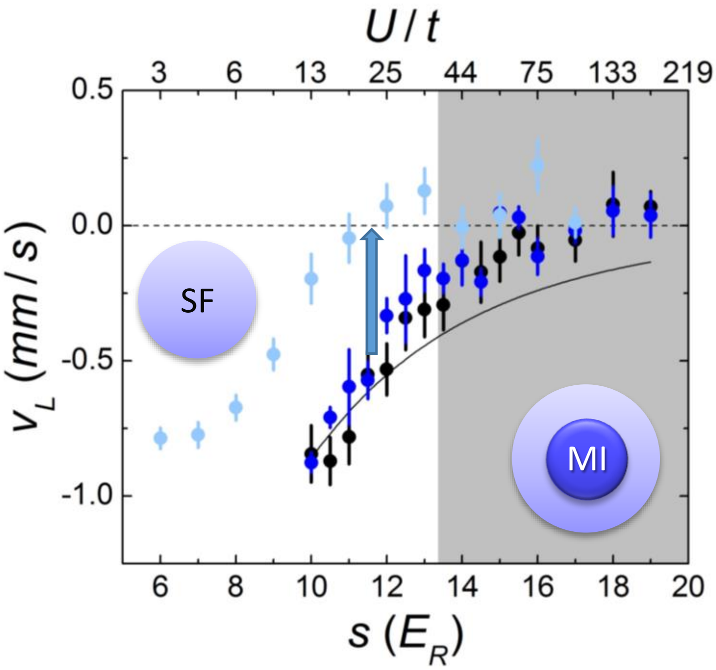

Figure 4. Transport measured in the disordered lattice for the superfluid and Mott insulator regimes. The arrow indicates the observed disorder-induced superfluid-to-insulator transition. The black point are for a clean lattice, and the dark (light) blue are for weak (strong) disorder.

3D Anderson localization

S.S. Kondov, W.R. McGehee, J.J. Zirbel, and B. DeMarco, Three-Dimensional Anderson Localization of Ultracold Matter, *Science* **334**, 66-68 (2011)

In separate experiments, we realized 3D Anderson localization (AL) for a non-interacting gas. Anderson localization is a phenomenon in which waves fail to propagate in a disordered medium. There are many open questions regarding AL in 3D, since all theoretical approaches to predicting AL fail precisely at the onset of localization. For these measurements, we used a spin-polarized, non-interacting gas of fermionic ^{40}K atoms. The gas was localized by releasing it into an optical speckle field (Fig. 5). These measurements we the first demonstration of 3D AL for quantum matter waves and the first experiments with ultracold fermionic atoms and disorder. By measuring how the fraction of atoms in the localized component changed at the speckle intensity and temperature was varied (Fig. 6), we systematically investigated how the mobility edge depends on the disorder strength (Fig. 7). These measurements will serve as a new benchmark for theoretical approximations.

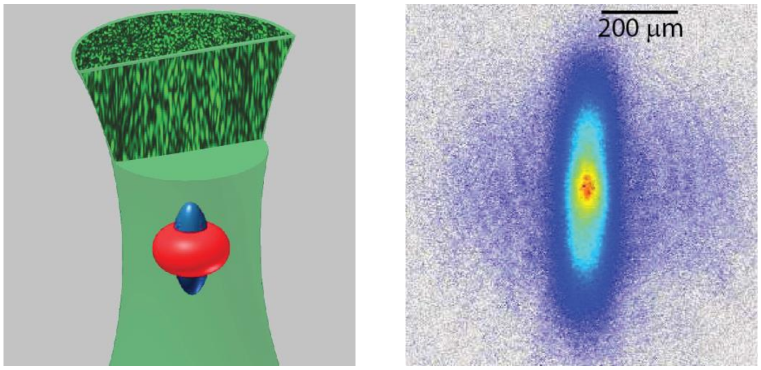

Figure 5. A spin-polarized gas of fermions is localized by allowing it to expand into an optical speckle field.

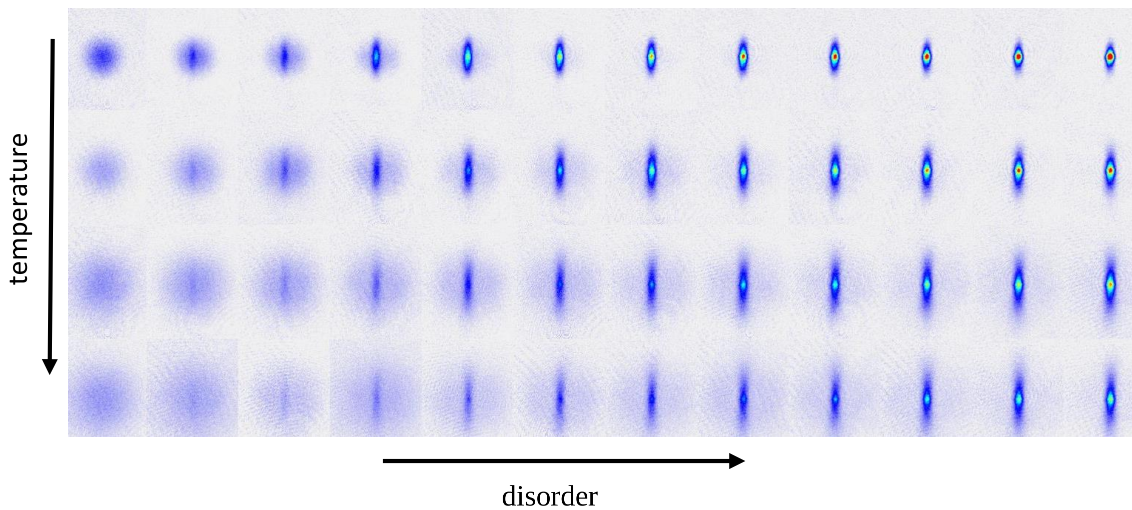

Figure 6. Images taken of the Anderson-localized gas as the temperature and disorder strength are varied. The number of atoms in the localized (narrow) and mobile (wide) components is used to infer the mobility edge.

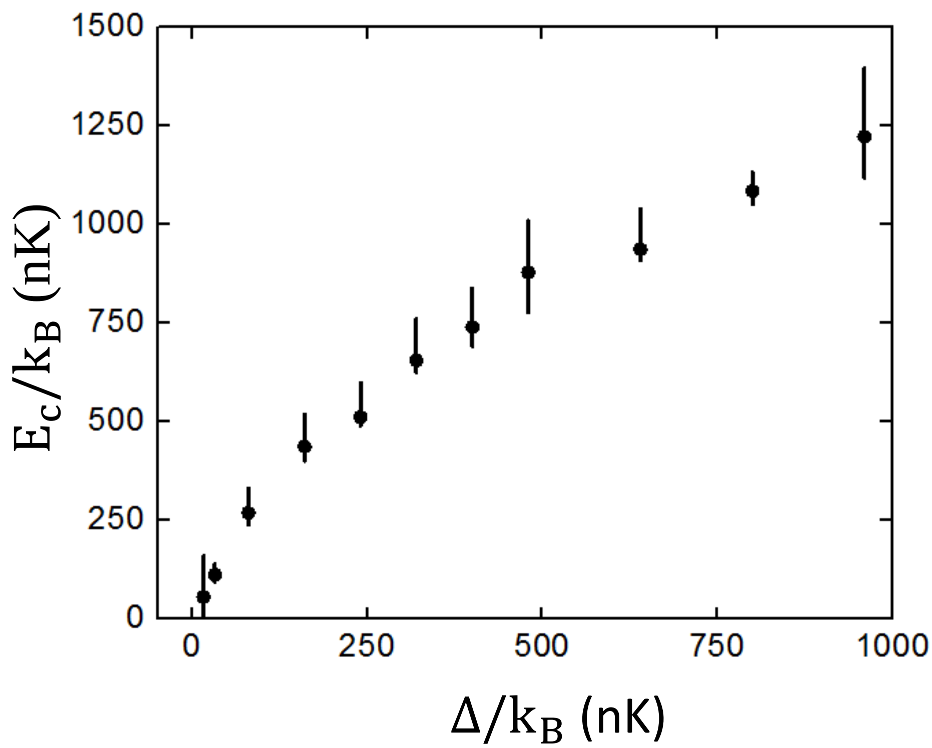

Figure 7. The mobility edge E_c is measured as the disorder strength is varied.

Spin-dependent lattices

Another focus area for work supported by this grant was spin-dependent lattices. In a spin-dependent lattice, the lattice potential depth—and hence the Hubbard tunneling and interaction energies—depends on the hyperfine state of the atoms. Spin-dependent lattices have promise for exploring exotic interacting spin physics in a lattice and for developing new methods for cooling lattice gases to lower entropy per particle. A fully 3D spin-dependent (cubic) lattice is a unique tool to our group that was developed under support by this grant.

Mixed Mott insulator–superfluid phases

D. McKay and B. DeMarco, Thermometry with spin-dependent lattices, *New Journal of Physics* **12**, 055013 (2010)

In these measurements, we used a spin-dependent lattice to realize mixed superfluid and Mott insulator phases. We created mixtures of $m_F = -1$ and $m_F = 0$ atoms. The $m_F = -1$ atoms experience the full lattice potential, while the lattice is absent for the $m_F = 0$ state (Fig. 7). The $m_F = 0$ atoms therefore realize a weakly interacting superfluid, while the $m_F = -1$ atoms achieve a Mott insulator phase for sufficient lattice depth.

Figure 8 shows images of each component as the lattice depth is varied; at high lattice depths, the trap is occupied by mixed superfluid and Mott insulator phases. Exotic spin phases are predicted in this regime at temperatures too low to currently be achieved in experiments.

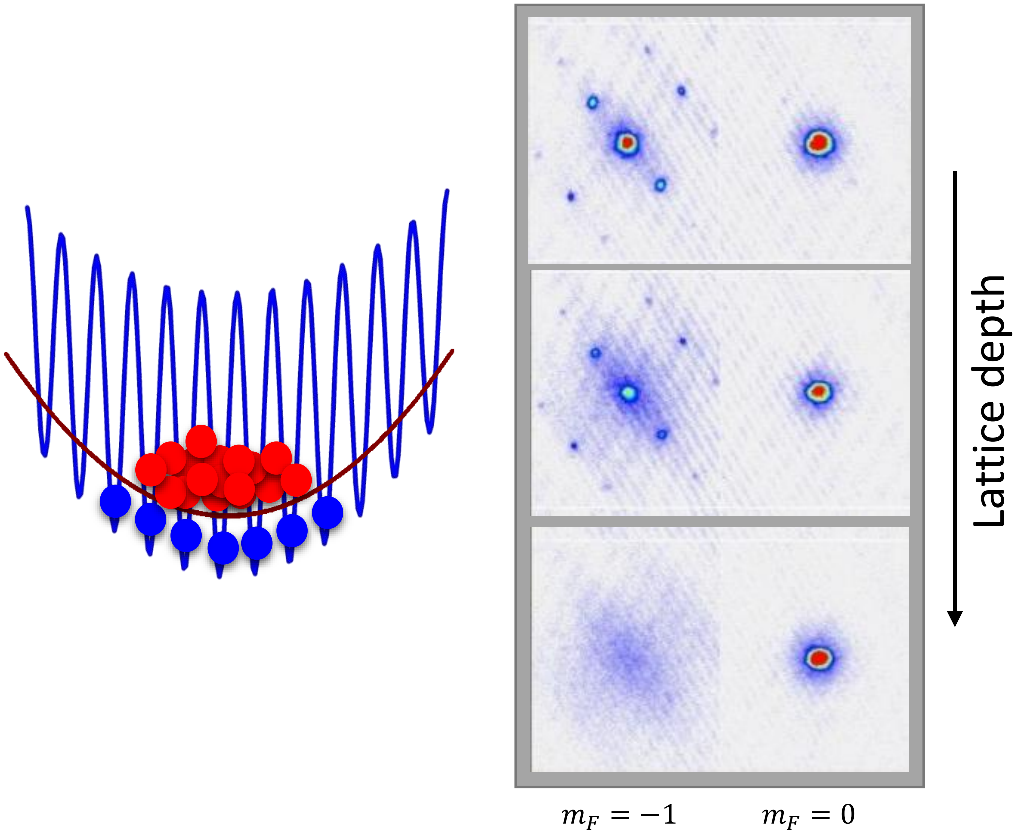

Figure 8. Two species are trapped in a spin-dependent lattice. The $m_F = 0$ atoms (red) do not experience the lattice potential, while the $m_F = -1$ atoms are lattice-bound. As the lattice depth is increased, the free atoms remain a weakly interacting superfluid, while the lattice atoms become a Mott insulator.

Anomalous thermalization

D. McKay, C. Meldgin, D. Chen, and B. DeMarco, Slow Thermalization Between a Lattice and Free Bose Gas, *Physical Review Letters*, in press (2013)

We also explored thermalization between the lattice-bound ($m_F = -1$) and free ($m = 0$) states in the spin-dependent lattice. By heating the lattice species to infinite kinetic temperature and then measuring the flow of heat to the free state, we measured the inter-species thermalization rate. We found that thermalization slowed down for higher lattice depths and became absent for a sufficiently strong lattice in the superfluid regime (Fig. 9). We showed that this effect is analogous to Kapitza resistance in a solid and arises from a mismatch in dispersion relations (i.e., energy and momentum cannot be conserved in inter-species collisions). This experiments represent a new technique for studying strongly correlated dynamics and are a critical element in a proposed lattice cooling scheme.

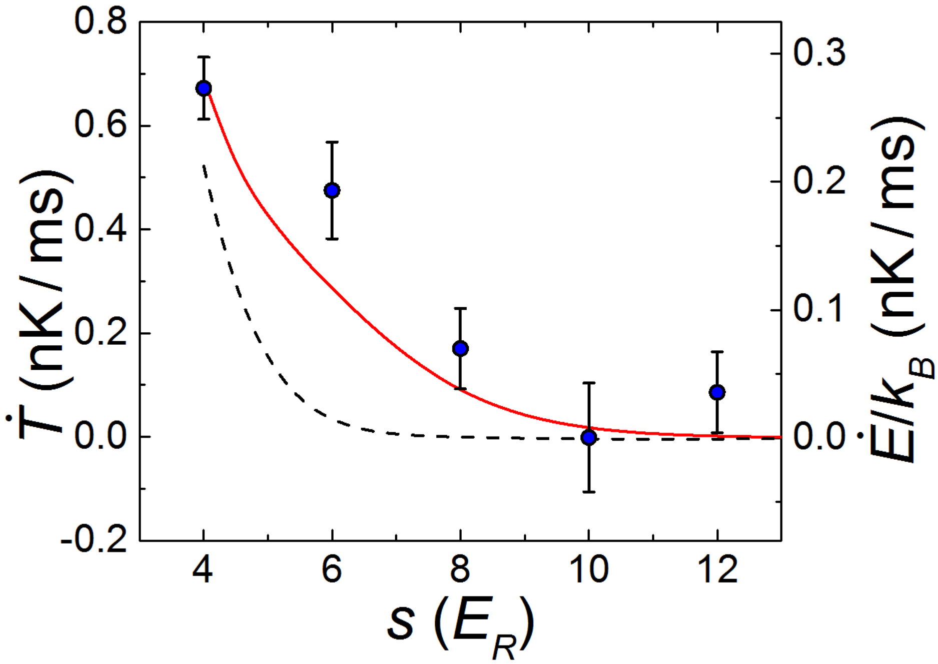

Figure 9. Thermalization rate measured for different lattice potential depths.